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Seismological research supported by Air Force contract F19(628)-68-C-0341 at the Lamont-Doherty Geological Observatory is summarized. The time spanned by the contract has seen existing advances in the use of long and intermediate period seismic waves for the identification of seismic sources in seismic instrumentation and in our understanding of global structures affecting seismic propagation. Our increased understanding of many features of the seismogram has enhanced its utility in detecting and identifying small seismic events. A large network of long and intermediate period instruments has been operated, and new high sensitivity, broad-band, low noise instruments have been developed which have proved especially effective for detecting and discriminating small events. Studies of seismicity and focal mechanisms for several tectonic regions and attenuation have provided additional support for the model of the New Global Tectonics. Study of the relative excitation of both body waves and surface waves by earthquakes and explosions have continued to reveal it to be a powerful discriminant between the two sources. Our understanding of earth noise has been extended to include all of the period range covering small seismic events. Thus important progress has been made toward detecting and identifying seismic events.

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RESEARCH DIRECTED TOWARD THE USE OF LONG & INTERMEDIATE PERIOD SEISMIC WAVES FOR THE IDENTIFICATION OF SEISMIC SOURCES

by

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INTRODUCTION

This report summarizes research carried on under the sponsorship of the Air Force Cambridge Research Laboratory and the Advanced Research Projects Agency through Contract F19(628)-68-C-0341 with the Lamont-Doherty Geological Observatory of Columbia University. In order to discuss this research in terms of the work statement of the contract, a copy of that statement is included in this report.

A list of publications supported by this contract during this period is attached to this report.

WORK STATEMENT

The work statement of contract F19(628)-68-C-0341 is as follows:

A. The contractor shall, unless otherwise indicated herein, supply the necessary personnel, facilities, services and materials to accomplish the following:

Line Item 1 - Operate and maintain the network of eight (8) widely distributed long- and intermediate-period stations formerly supported under contract AF19(628)-4082 to furnish data for seismological investigations related to the detection and identification of earthquakes and underground nuclear explosions. These stations by name and code are Palisades, N.Y. (PAL); Sterling Forest, N.Y. (SFO); Huancayo, Peru (HUA); Honolulu, Hawaii (HON); Mount Tsukuba, Japan (MTJ); Bokaro, India (BOK); Canberra, Australia (CAN); and one to be determined during the contract period. Changes in the numbers and locations of the stations are not to be made without prior written approval of the Contracting Officer. Investigations using data for these stations and other data sources (e.g. Montana and Norway LASA's, VELA-UNIFORM observatories, WWSSN, etc.) shall consist of but not be limited to the following:

Sub-Line Item 1AA - Extend the studies of the relative excitation of body and surface waves by earthquakes and underground explosions to small magnitude events. Determine discrimination thresholds both theoretically and empirically.

Sub-Line Item 1AB - Investigate the general characteristics of seismograms, such as the presence or absence of phases, dominant periods, duration, etc., as a function of source mechanism, region, focal depth and radiation pattern, and the relation of these features to the problems of detection and identification of seismic events. Emphasis should be placed on studied of the PL and compressional and shear coupled leaking modes, the depth phases, and multiples of P and S and on methods to selectively enhance these phases.

Sub-Line Item 1AC - Conduct detailed seismicity studies of geographic areas of interest to the VELA-UNIFORM program.

Sub-Line Item 1AD - Investigate the LASA amplitude and travel-time anomalies.

Sub-Line Item 1AE - Develop seismic instrumentation to increase sensitivity in the long-period range and improve discrimination against noise in the dominant microseism band.

Sub-Line Item 1AF - Develop techniques for analyzing microseismic data and conduct studies of microseismic data.

Sub-Line Item 1AG - Investigate aspects of the New Global Tectonics that are of particular relevance to the problems of detection and identification of seismic events and to the problem of predicting optimum siting of seismic stations, networks and arrays.

Sub-Line Item 1AH - Conduct studies of near earthquakes and explosions to determine properties of the source, of the propagation path and of the crust and upper mantle in the vicinity of LASA arrays.

Sub-Line Item 1AJ - Conduct detailed studies of wave propagation, of source characteristics, and of surface and body waves of short and long periods originating at teleseismic distances with particular emphasis on regions with complicated crust and mantle structure.

MAJOR ACCOMPLISHMENTS

Item 1. Operation of the Lamont-Doherty network of eight long- and intermediate-period seismic stations, including the Palisades, Sterling Forest, and Ogdensburg stations, has continued during the past year.

1AAa. Relative excitation of body and surface waves by explosions and earthquakes. During the past year two programs have been conducted conceming the use of the relative excitation of seismic waves as a diagnostic aid for discriminating earthquakes from explosions.

The first of these used the new high-gain, wide-band, long-period seismographs to study surface waves from events in western North America. With this instrument, events with surface wave magnitudes proved to be a very effective diagnostic aid for discdminating earthquakes from explosions at these large epicentral distances. Moreover, very pronounced differences in the Rayleigh wave spectra were observed for earthquakes and explosions. For a given amplitude of 15 to 25 second waves, the 40 to 60 second waves were much larger for earthquakes than for explosions. This observations provides another diagnostic aid for discrimination. The results demonstrate that these new instruments may provide a major advance in the detection and discrimination of seismic events (other results from the ultra high-gain instruments are discussed under Item 1AE). A paper entitled "Small Earthquakes and Explosions in Western North America Recorded by New, High-Gain, Long-Period Seismographs" by Peter Molanr, Lynn

R. Sykes, John Savino, George Hade and Paul W. Pomeroy was published in Nature.

In the second program, the relative excitation of long-period and short-period P waves from underground explosions and shallow earthquakes was studied. The ratio of P waves recorded by the long-period and short-period instruments of the WWSSN indicated a noticeable difference between underground explosions and shallow-focus earthquakes, but it was also determined that the difference between the two ratios is magnitude dependent. For body wave magnitudes of 5.5 or greater, the relative excitation of long-period P waves of an earthquake was at least 10 times greater than that of an underground explosion, but this difference drops to 2 to 5 times for magnitudes less than or equal to 5.0. Such changes in relative excitation can be explained by differences in source dimension between shallow-focus earthquakes and underground explosions. Similarly computed ratios for P waves from deep-focus earthquakes fell between ratios calculated for shallow-focus earthquakes and those of underground explosions; providing additional information concerning the relationship between source dimensions and relative excitation of P waves.

1AAb. Long-period noise study. During the past year the investigation into the source of long-period earth noise operative at the mine observatory in Ogdensburg, New Jersey, was continued. Data from a high-gain vertical component long-period seismograph system and a microbarograph located near the surface at Ogdensburg together with data from the underground instruments yielded conclusive evidence that for periods longer than 30 sec, nonpropagating ground motion of atmospheric origin is the primary constituent of earth noise.

Of particular interest to the problem of nuclear event detection is the mechanism whereby the atmosphere generates earth noise. The investigation at Ogdensburg indicates that this mechanism is static loading of the earth's surface by random variations in atmospheric pressure. The 60 sec portion of the earth noise spectrum is influenced by atmospheric sources as far away from the observatory as 50 km. We have concluded that any attempt to enhance the seismic signal-to-noise by cancellation of seismic and microbaric signals recorded at one location will not work. However, the random nature of the loading sources and estimates of their dimensions indicate that recordings of earth noise at periods less than about 60 sec made on instruments separated by 5 km will be incoherent. In this case the signal-to-noise ratio can be enhanced by the familiar N factor where N is the number of instruments.

A paper describing these results has been written and is titled: The nature of long-period (20 to 130 sec) earth noise and importance of a pronounced noise minimum to detection of seismic events. This paper has been submitted as a Ph.D. thesis by John Savino and has been accepted by the Journal of Geophysical Research in abbreviated form by John Savino, Keith McCamy, and George Hade.

1AAc. Acoustic gravity waves. On 14 October 1970 ground motion induced by acoustic-gravity waves with periods between about 40 and 200 sec were recorded on the three-component set of high-gain seismographs at Ogdensburg. These waves were excited by an event presumed to be a Chinese atmospheric explosion which occurred on the same day at 07h 29m 58.6s and was assigned coordinates of 40.9N, 89.4E by the U.S.C.G.S., P.D.E.

A striking feature of these air waves as seen on the seismograms was their very high signal-to-noise ratio. In fact, the S/N for this event was 3 to 5 times higher on the high-gain seismograms than on barograms for a 4-element array of microbarographs operated near Lamont. The mine site acts as a filter for incoherent atmospheric noise but passed the coherent acoustic gravity waves from the Chinese event. In this sense the seismographs and mine act like an array of microbarographs. Thus, the high-gain instruments must be considered as a type of very sensitive microbarograph and will be extremely useful for monitoring atmospheric events. In addition, even if air waves from an atmospheric explosions and seismic waves from an earthquake were to arrive at Ogdensburg at the same time, the longer-period air waves could be easily separated by digital low-pass filtering.

A letter describing the October 14 air waves recorded at Ogdensburg and Charters Towers, Australia is in preparation. The title of this letter is "Acoustic-gravity waves recorded on very sensitive seismographs," by John Savino and John Rynn.

1AAd. During the year, using data from the high-gain seismograph systems at Ogdensburg, New Jersey, a study of the excitation of long-period (15-70 sec) Rayleigh and Love waves by earthquakes, and presumed explosions was analyzed for four different regions of the world; western United States, The Aleutians, Novaya Zemlya, and central Asia. The most significant result of this study is that in all four regions discrimination between these two types of events based on a comparison of surface-wave magnitude (M_s) and body-wave magnitude (m_b) is enhanced when surface waves with periods near 40 seconds, rather than 20 seconds, are used in the determination of M_s. For constant m_b the difference in Rayleigh wave amplitudes between the mean of the earthquakes and explosion populations at 40 seconds is as much as four times greater than the difference at 20 seconds.

The amplitude spectra of Rayleigh waves in the period range 15-60 sec fall off faster at the longer periods for presumed explosions than for earthquakes in the western United States and the Novaya Zemlya region. These data suggest that although depth of focus and radiation pattern may be important in shaping the surface wave spectrum and causing differences between earthquakes and explosions, differences in the source time function are also likely. The Rayleigh wave spectrum from the underground explosion Milrow, on Amchitka Island in the Aleutian earthquakes or the release of tectonic strain associated with

Milrow (i.e., large 40-sec Love waves observed at Ogdensburg from Milrow) resulting in a possible earthquake contamination of the assumed explosion spectrum.

A paper describing this work is in the final stage of preparation.

1AAe. Triggering of microearthquakes by underground explosions. A field party went to Nevada in early 1968 to study microearthquake activity in the vicinity of the Nevada Test Site, particularly to investigate the possibility that earthquakes may be triggered by large nuclear explosions. Six portable, high-gain instruments were operated from about 85 to 160 km northeast of the site of the nuclear explosions. The purpose was to see if the background activity of this region changed following the explosion. Background activity was low before the detonation; one to two microearthquakes, with magnitude between about 0 and -1, were recorded per day within 25 km of each site. Similar activity was recorded after the shot. Microearthquake activity in Death Valley, California, was also low after the detonation of Benham, suggesting that this explosion did not substantially affect the background activity there. A paper concerning this study, entitled "Microearthquakes in eastern Nevada and Death Valley, California before and after the nuclear explosion Benham," by Peter Molnar, Klaus Jacob and Lynn R. Sykes has been published in the December 1969 issue of the Bulletin of the Seismological Society of America.

1AAf. Source dimensions of small earthquakes. Data derived from studies by other workers of prominent, well-defined aftershock sequences are employed to obtain evidence for the source dimensions of earthquakes in the magnitude range m = 4 1/2 to 6. The characteristic length of the aftershock zone is defined as the longest dimension of the map view of the aftershock epicenters. On the basis of this aftershock data, the following rough limits may be placed on the likely size of small earthquakes in the western United States; for magnitude 5 events, 5 to 25 km; for magnitude 4 events, 2 to 15 km. These limits are about an order of magnitude larger than those proposed by Press for earthquakes and underground explosions and represent an independent confirmation of the results for earthquakes of Wyss and Brune. The larger dimensions suggest that differences in the seismic spectra of earthquakes and underground explosions should persist even for some events as small as m = 4. These results have an important bearing on recent studies of the excitation of surface waves by earthquakes and underground explosions.

1ABa. P wave spectra from underground nuclear explosions. A study of P-wave spectra was undertaken to investigate the causes of spectral differences observed in seismic waves generated by underground nuclear explosions and earthquakes. The spectrum of surface wave depends on the depth of focus of the source, but a radiated body-wave

spectrum is independent of focal depth; thus P waves from both types of source were compared. Pronounced differences in the P-wave spectral content from these two sources were discovered. P-wave spectra recorded at teleseismic distances from underground explosions are a maximum at periods of 2 to 4 seconds and decrease rapidly at longer periods. Earthquakes with similar body-wave magnitudes, however, have spectra that increase to a maximum at periods greater than about 5 seconds and may remain flat at longer periods.

The sharp decrease in the explosion-generated P-wave spectrum at long periods is, at least in part, a consequence of the surface reflection. The reflected phase, pP, essentially differentiates the radiated P wave and thus diminishes the long-period portion of the spectrum. An impulsive source-time function for the explosion would also enhance the shorter period portion of the signal. In fact, the observed decrease in the spectrum for explosions is consistent with an impulsive source-time function. When a step source-time function is assumed, however, an estimate of the dipole moment of the explosive source based on the P-wave spectrum at 2 to 3 sec period is of the same order of magnitude as that based on the Rayleigh-wave spectrum in the band near 50-sec period. This result suggests that the source-time function for the explosions studies is not grossly different from a step function.

In addition, the pronounced difference in spectral content of P waves from earthquakes and underground nuclear explosions suggests a method for identification that is applicable for explosions large enough to be recorded by long-period seismographs at teleseismic distances. This method may be particularly important when long-period instruments are disturbed by other events and methods of identification that rely on analysis of surface waves become inapplicable.

A paper on this subject titled "P wave spectra from underground nuclear explosions" by Peter Molnar has been submitted for publication in the Journal of Geophysical Research. The results were also presented in a paper by P. Molnar, T. Matumoto, and J. Savino at the annual meeting of the Seismological Society of America in Milwaukee, Wisconsin, November 1970.

1ABb. Shear-coupled PL waves. A paper summarizing the work on oceanic shear-coupled PL waves has been prepared for publication. The major conclusions of the paper are that two classes of oceanic shear-coupled PL waves are observed. The waves of the first class have periods between 10 and 20 seconds and are most frequently observed at between 30° and 55° from the epicenter. The oceanic crust is involved in the propagation of the PL wave. Waves of the second class have periods between 20 and 60 seconds and are observed at between 60° and 85° from the epicenter. A wave guide thicker than the oceanic crust propagates the leaking mode in this case. These conclusions were arrived at after an extensive scanning of WWSSN seismograms and comparison between the observed seismograms and synthetic seismograms.

A paper describing the mathematical theory of transient leaking modes is nearly completed. This paper draws attention to certain unsatisfactory features of the leaking mode theory as reported in the literature, particularly in reference to the significance of dispersion curves of leaking modes. The results of this paper were useful in the observational paper mentioned in the preceding paragraph.

The understanding of the shear-coupled PL wave phenomenon provided by these papers and those of Chander, Alsop and Oliver (1968, Bull. Seism. Soc. Am.) and Oliver (1961, Bull. Seism. Soc. Am.), particularly with respect to the differences and similarities of shear-coupled PL waves for oceanic and continental paths, will be useful in designing matched filters for detecting small seismic events.

1ABc. Leaky modes. A paper entitled "Leaky modes - a ray theory approach" has been published. The paper demonstrates that the ray model for leaky modes proposed by Burg et al. yields an inhomogeneous wave and the physical structure of the leaky mode can be better understood. Since the mode is generated by long-period compressional and shear waves, the possibility exists of using spectra from direct and shear-coupled PL modes for identification criteria.

1ACa. Seismicity of the Aleutians. A study of the occurrence of large shallow earthquakes in the Alaskan-Aleutian seismic zones was completed. The results of this investigation were published in the October 15, 1970 issue of the Journal of Geophysical Research. This paper is entitled "Space-time seismicity of the Alaska-Aleutian seismic zone." This study indicates that major earthquakes of this zone tend to progress in time from east to west. Extrapolation of past trends indicates that a major Alaska-Aleutian earthquake will probably occur near 56N, 158W between about 1974 and 1980.

Three kinds of evidence indicate that earthquakes of about magnitude 7.7 and larger should be used to identify space-time earthquake patterns in the Alaska-Aleutian seismic zones: (1) space-time graphs of earthquakes of about magnitude 7.7 and larger show strong linear trends; (2) aftershock zones of successive large earthquakes ($m \geq$ 7.7) are approximately adjacent; (3) the direction of fracture propagation is generally away from the focal zone of the previous adjacent large earthquake. This suggests that the concentration of stress prior to the event was greatest near the region of the adjacent earlier earthquake. Since this pattern is reasonably consistent, the linear trends of large earthquakes in this seismic zone are probably due to some physical phenomena rather than some unusual chance distribution.

The space-time distribution of the USCGS epicenters for 1961-1967 suggest that these past trends will continue. These epicenters show a distinct seismicity gap in the region predicted for a major Alaska-Aleutian earthquake. In the past, such gaps have often occurred before major earthquakes.

1ACb. Earthquake sequence associated with the eruption of Volcan Arenal, Costa Rica. An earthquake sequence with an explosive eruption of Volcan Arenal, Costa Rica, has been studied to seek the diagnostics for distinguishing volcanic earthquakes from explosions. Despite the similarity of shallow, pressure-type origins, the difference in the temporal sequence of the stress accumulations and complication of the local geological circumstances near the volcano provide the following diagnostic features for the volcanic earthquakes:

1. A swarm of earthquakes occurred approximately 9 hours prior to the first major eruption. The time sequence of the earthquakes was obviously different from that of tectonic aftershock sequence; this activity apparently started with relatively minor earthquakes which then increased in intensity and frequency. After a series of major eruptions, the seismic activity declined rapidly.

2. Combined total of approximately 10^{18} ergs of energy have been released by a swarm of earthquakes. Compared with the total of 10^{22} ergs of thermal, kinetic and potential energy associated with the eruption, only a small fraction of energy has been released by the earthquakes.

3. The total volume of the volcanoes that have been destroyed by the eruption was 5×10^{14} cubic cm. It is noticeable that the seismic energy released prior to the eruption is comparable with the strain energy that may have been accumulated in this destroyed volume (the estimated strin energy: 1.25×10^{18} ergs).

4. The log-log plot of the frequency vs. trace amplitude shows a higher B-value (the slope of the curve) of 2.25 compared with those for tectonic earthquakes which range from 0.5 to 1.2.

5. Two different types of the seismic signatures have been observed. The first type resembles that of a tectonic earthquake, which begins with a clear P phase and is followed by S phase. The second type, however, exhibits a unique appearance. An earthquake begins with emergent onset which then increases in amplitude without showing any distinguishable phases. The latter appears only in the immediate vicinity of the active vent and the depth of the source is usually less than 1 km.

1ACc. ESSA, USCGS, epicenter data, 1961-1967. A manuscript entitled "World seismicity maps compiled from ESSA, Coast and Geodetic Survey, Epicenter Data, 1961-1967" was published in the February 1969 issue of the Bulletin of the Seismological Society of America. This paper presents world seismicity maps with almost 30,000 events on them.

The same epicenter information has been stored on a magnetic disk to allow more rapid access to the data than with magnetic tapes.

This epicenter data is being used to study spatial and temporal statistics of earthquakes before and after major earthquakes. Preliminary analysis involved computation of pairs of b values (from the formula log $N=a-bM$ where N is the number of earthquakes of magnitude M or greater) before and after major earthquakes. This has been done for 40 earthquakes around the world. In all but 5 earthquakes, the b values before and after the earthquake are similar. The 5 exceptional earthquakes occurred in the circum-Pacific belt; for them, smaller b values before the earthquake are associated either with the existence of foreshocks or with a general increase of seismicity. A possible correlation between the time-decay factor and the b-value of aftershocks is indicated.

For the above 40 earthquakes, plots of numbers of aftershocks versus distance from the main shock define the boundaries of aftershock zones clearly. For a given magnitude, the radius of the aftershock zone obtained in this analysis is systematically smaller than the radius obtained by Utsu.

The importance of such studies to VELA-UNIFORM lies in the fact that the spatial and temporal clustering of events may provide diagnostics for distinguishing between earthquakes and explosions.

1AE. Ultra high-gain, long-period instrumentation. Ultra high-gain, wide-band, long-period seismograph systems have been developed to aid in the detection and discrimination between small (m_b=4.0) earthquakes and underground explosions at teleseismic distances. Maximum operating gains of 330k at 40-50 seconds allow discrimination between small earthquakes and underground explosions based on spectral differences of 20-70 second surface waves from these events. Such high-gain operation is possible as a result of rigid environmental control: (a) operation in a deep mine (1850' level), and (b) instruments housed in pre-stressed hemispherically topped tanks behind a series of three ship-type bulkhead doors.

With completion of the installation of these instruments, efforts to determine the cause of and possible reduction of observed noise level have been made. Experiments with matched vertical instruments in different sections of the mine observatory and instrumental noise checks indicate the presence of two components of noise responsible for the observed background level (15-200 seconds).

a. 15-25 second propagating microseismic activity (amplitude variations up to 20 db)

b. 25-200 second, a predominant coherent source and the long-period galvanometer noise. The ratio of coherent to galvanometer noise is approximately 2 to 3.

At the present time attempts are being made to reduce the effect of both noise sources in the 25-200 second range, and further increase the detection capability of these instruments.

In conclusion, the successful operation of a three-component set of long-period seismometers at ultra high-gains is due to the careful installation and rigid control of the noise producing environmental factors,e.g. temperature, pressure, and humidity.

1AF. The problem of the sources of the various components of the earth noise has been addressed, using data from LASA, and, to a large extent, solved. It was found that the dominant fundamental mode Rayleigh waves are generated almost exclusively by wave action at coast lines, with generation by moving storm centers at sea limited to the rare storms that move faster than ten degrees per day. Fundamental mode Love waves share the same directional properties as the Rayleigh waves and most likely a common source. The body wave component of the noise,which becomes noticeable at frequencies about 100 MHZ, is generated both by storms at sea and by storms near the coast. The wakes of storms at sea are prominent sources of body waves at frequencies well above the cut-off frequency, $f_{cutoff}=g/2\ v$, where v is the speed of the storm and g is the acceleration of gravity. Higher mode Rayleigh waves are often associated with the same storms that produce fundamental mode Rayleigh waves but for some reason do not come from the west or northwest. A paper describing this work, "Microseisms: coastal and pelagic sources" by R.A. Haubrich (IGPP, La Jolla) and Keith McCamy (Lamont), appeared in the Reviews of Geophysics.

1AGa. Three dimensional seismic ray tracing and P residuals. P travel time residuals of the Longshot nuclear explosion were calculated using Cleary-Hales P-travel times for reduction, compared to the Herrin P68-travel times used in a previous study, to investigate the effect of the travel time standard used on the pattern of residuals. From the observed P residuals the near-source term was eliminated by data obtained from realistic model calculations using three-dimensional seismic ray tracing. Elimination of the near-source term residuals yields residuals caused primarily by heterogeneities in the crust and upper mantle near each seismic station. Tectonic grouping of these station residuals (shields, continental, oceanic, tectonically inactive and active regions) showed significant correlation similar to that obtained when using P68-travel times for reduction. Stable continental shields showed P arrivals that are at least 2 seconds earlier than P in tectonically and volcanically activeareas. Although the relative differences in the tectonically grouped residuals were practically the same for reduction with C-H and P68-travel times, there emerged a significant shift of the average level.

1AGb. Fifty new focal mechanisms have been determined for earthquakes in the New Guinea, Bismarck Archipelago, Solomon, and Hebrides areas. These solutions show that the Pacific and Australian plates are converging in a northeast to southwest direction. A new, very small plate is defined in the region of the southern Bismarck Sea. The consistent relative motions of the Bismarck, Australian and Pacific plates show that plate tectonics is applicable even for regions with dimensions of a few hundred kilometers.

1AGc. Attenuation of the Sn phase. A study has been conducted of the gross characteristics of over 1500 Sn phases traversing different paths throughout the world. Sn is a short-period shear wave that travels in the upper mantle at a constant surface velocity of about 4.7 km/sec. For different paths, the character of these waves varies dramatically from being totally absent for some paths to being rich in frequencies higher than 2 cps for others. In general, Sn propagation is most efficient across stable regions such as continental shields, deep ocean basins, and along the inclined zones of earthquakes in island arcs, but is poor across the concave sides of island arcs and along crests of mid-ocean ridges. The point of great relevance to the VELA-UNIFORM that emerges from this study is that the capability of seismic arrays and high magnification seismographs for detecting distance seismic events will be greatly increased if future arrays and individual seismographs are located in regions where the attenuation of waves under and near the stations is minimal or in regions where the body waves reemerge at the surface after travelling down the zones of low attenuation under island arcs. The study is a first comprehensive attempt to map such areas. A paper discussing this study has been published in the Journal of Geophysical Research.

1AGd. Focal mechanisms. During the period under report, several studies have been conducted of the seismicity and focal mechanisms of earthquakes in several tectonic regions. From these studies, strong support has been found for the model of the New Global Tectonics based on sea-floor spreading, continental drift and movement of large plates of the earth's surface. The importance of the focal mechanism studies to VELA-UNIFORM is that as a result of a large number of such determinations at Lamont and similar studies at other institutions, it has become exceedingly clear that earthquakes are predominantly double-couple type sources rather than pure explosions. A remarkable consistency in the orientations of focal mechanisms has been found for events in a given region. Also, one of the advantages of relocating earthquakes is to delineate the zones of naturally occurring seismic (i.e. earthquakes) precisely and to thus help in identification of man-made seismic events. Some of the results of these studies are:

1. A paper entitled "Tectonics of the Caribbean and Middle America regions from focal mechanism and seismicity" by Peter Molnar and Lynn R. Sykes, published in the Bulletin of the Geological Society of America, September 1969. This paper discusses the tectonics of the region in terms of larger plates of lithosphere and demonstrates the consistency of recent ideas of global tectonics for relatively small plates.

2. A paper entitled "Seismicity and tectonics of the western Pacific: Izu-Mariana-Carolina and Ryukyu-Taiwan regions" by Mamoru Katsumata and Lynn R. Sykes, published in the Journal of Geophysical Research,

discusses the results of relocating the hypocenters of about 1000 earthquakes; in addition, earthquake mechanism solutions based on the first motions of P, pP, and S were determined for 26 earthquakes. The spatial distributions and focal mechanisms of these earthquakes are compared with major tectonic features, such as volcanic zones, island arcs, and trenches in the studies regions.

3. A paper entitled "Mantle earthquake mechanisms and the sinking of the lithosphere" by Bryan Isacks and Peter Molnar was submitted to Nature. This paper demonstrates a consistent pattern in the orientation of the inferred principle stress axes for intermediate and deep earthquakes. For nearly every deep earthquake the inferred axis of maximum compression (P axis) was aligned parellel to the dip of the inclined seismic zone. Where the seismic zone is continuous from the earth's surface to 600 km, the P axis is parallel to the dip at intermediate depths also. However, in regions where there is a pronounced gap in the inclined seismic zone or where there are no deep earthquakes at all, often the inferred axis of tension (T axis) is parallel to the dip of the zone. Thres data support the concept of the lithosphere as a stress guide.

4. A comprehensive study of seismic activity along the Alpine-Himalayan orogenic belt east of the Hindu Kush is nearing completion. The study has lead to a more realistic model of near surface tectonics. Zones of shallow, intermediate, and deep focus activity are better defined and reliable focal mechanisms from shallow focus earthquakes define modes of brittle deformation. Recent seismicity data suggest that the shallow focus seismic zones are continuous while the intermediate and deep focus zones are clearly discontinuous. This result is consistent with the "new global tectonics" model in which most shallow focus seismicity is located on the boundaries of interacting plates of lithosphere. Some modifications in simple plate theory, based on the idea of rigid plates, are needed to explain the activity in complex tectonic regions such as the region between New Guinea and the Celebes. It is hoped that continual improvement in the model for near surface tectonic activity will eventually result in more accurate prediction of spatial and temporal distribution of shallow focus earthquakes.

It is planned to publish this work in three parts:

a. A paper on the shallow focus activity in the Indonesian-Philippine region including 43 new focal mechanism determinations.

b. A paper on intermediate and deep focus activity in the same region including 28 new focal mechanism determinations.

c. A short paper on the current seismicity of the Himalayan and Burmese regions.

1AHa. Mantle Rayleigh waves using long-period LASA data. A "phase-equalization and sum method" was employed for processing long-period mantle Rayleigh wave data from the Montana Large Aperture Seismic Array (LASA). Vertical component seismograms were analyzed for periods longer than 50 seconds. The usefulness of this method was clarified through tests for both seismic events and noises. Individual records are dominated by instrumental and environmental noise plus other long-period noise at very long period. Advantages of this method are: (1) signal to noise amplitude ratio was increased by 8 db for period of 5o to 100 seconds, 10 db in the 100 to 200 second period and 5 db in the 500 sec period; and (2) fidelity correlation between sensors after application of the phase equalization and sum method, (3) deviations due to each station are expected to be reduced by 1/N times, where N is the number of stations used. Two large earthquakes (M=6), in Mongolia and near Taiwan, were analyzed and dispersion curves were obtained in the period range 50 to 300 seconds and 50 to 160 seconds, respectively. In addition to the usefulness of the phase equalization and sum method, the reliability of LASA long-period digital data is shown. This technique greatly enhances coherent long-period seismic waves and reduces the effects of seismic and environmental noise which is largely incoherent at periods greater than 50 sec.

A paper "Mantle wave analysis by phase equalization and sum method for Montana LASA long period data" by K. Hamada is in press.

1AHb. Solving the elastic wave equations by the methods of finite differences. A program has been written and completely debugged for solving the elastic wave equations by the method of finite differences. The equations used are suitable for heterogeneous media. The elastic properties of the medium and the source characteristics are inserted through subroutines. The initial experiments have involved the propagation of Rayleigh waves through a heterogeneous rectangular parallelopiped. A Rayleigh wave excitation function is applied at the edge of the parallelopiped in a homogeneous region and then allowed to propagate into a heterogeneous region.

Such numerical techniques are necessary for solving three-dimensional problems which are now amenable because of the detailed earth model provided by the New Global Tectonics. For example, it will be possible to take account of three dimensional variations in the earth structure under LASA when considering elastic wave propagation under and across the array. A paper entitled "Solutions of elastic wave equations by finite differenc methods" was presented at the Eastern Section of the Seismological Society of America in October 1968. An expanded version of this paper is now in press by the Reviews of Geophysics.

1AJa. Rayleigh wave amplitudes. Two manuscripts were published that have important bearing on the feasibility of monitoring surface waves from distant seismic events using high-gain, long-period seismographs located in a tectonic province different from that of the seismic event.

In the first study of seismograms from Berkeley and OBS III (a seismograph on the deep ocean bottom 235 km WNW of Berkeley) were compared to ascertain the effect on Rayleigh waves of propagation across the continental margin. Spectral amplitude ratios in the period range from 14 to 25 seconds and for near-normal incidence show that amplitudes of vertical displacement on the ocean bottom were 2/3 to 1/3 as large as those at Berkeley. Comparing these with theoretical ratios calculated by a variational technique suggests that there is a striking contrast in structure between Berkeley and OBS III. Velocities and densities of the lower crust and upper mantle beneath the oceanic site are much higher than those beneath Berkeley.

In the second study, amplitudes of the vertical component of 20 second Rayleigh waves were measured at 25 WWSSN stations in the United States; the Rayleigh waves were produced by shocks in the Pacific Ocean and on the mid-Atlantic ridge. Amplitudes were plotted as a function of azimuth from epicenter to station and on outline maps centered on the epicenters. Patterns of surface wave amplitude are highly sensitive to epicentral location and change continuously with change in epicenter. The amplitudes generally show variations of a factor of 10 or more within the array. These striking fluctuations of amplitude appear to be largely produced by focusing caused by lateral variations in phase velocity. A simple model of a horizontal variation in phase velocity explains the size and character of the most prominent variations in amplitude. The most reliable estimates of amplitude are those measured at sites closest to the seismic events; amplitudes of Rayleigh waves from distant events measured at a single array such as LASA may be very unreliable because of possible effects of lateral refraction. Although they were not studied extensively, the amplitudes of long-period P waves do not appear to exhibit as large a scatter as the amplitudes of the 20 second surface waves.

1AJb. Source size of mid-ocean ridge earthquakes. It has been observed that the Rayleigh wave trains from certain earthquakes originating on the mid-ocean ridges show the normally dispersed oceanic Rayleigh waves superimposed on the inversely dispersed Rayleigh waves of periods between 40 to 90 sec, while others show only shorter-period Rayleigh waves. Since earthquakes on mid-oceanic ridges are of shallow focus, the long-period waves must have been excited by sources of abnormally large size. The earthquake of 14 February 1963 on the mid-Atlantic Ridge has been selected for a detailed investigation of the source size. Copies of the WWSSN seismograms for this event were prepared for digitization and Fourier transform analysis of Rayleigh waves; the analysis will be carried out in the near future. Such studies of the source size of earthquakes are of interest in distinguishing nuclear explosions and earthquakes using observed seismic signals.

1AJc. Discrimination of earthquakes and explosions by a master event technique. A recently started study of discriminating earthquakes from nuclear explosions for a given source region by a master-event

technique was continued. Using an explosion or earthquake with a well-known focal mechanism as a master event, the observed phases of Rayleigh waves at many different periods from events in question may be compared with the master event. Because of the radial symmetry of radiation of explosions and asymmetric radiation from earthquakes, a difference in the azimuthal distribution of phase spectra can be expected. Presently the method is tested using a selection of nuclear explosions from the Nevada Test Site. A list of earthquakes that have occurred since 1962 with epicenters less than 1° away from the Test Site is checked for application of this method. The first detailed analysis is expected to be carried out on seismograms of all three components on 25 WWSSN long-period stations recorded from the BOSCAR explosions, its cavity collapse and two earthquakes from nearby.

1AJd. A theoretical study of surface wave dispersion in a mass loaded half-space has been completed. The effect of a layer on surface wave propagation on a half-space can be separated into the terms arising from elastic and from inertial restraining forces. In a number of situations of practical importance, it turns out that the inertial forces are dominant. The period equation governing the dispersion for this pure mass loading were obtained in suitable form and numerical solutions for Rayleigh waves both for solid and fluid loading are obtained. It is shown that by presenting the results in terms of appropriate normalized variables, extremely simple approximately linear dispersion characteristics are found. A single computation suffices for substrate materials having the same Poisson ratio. The validity of this approximation is explored for modified Rayleigh waves for both solid and liquid layers and for Love waves.

A paper reporting on this work is being prepared for submission to the Journal of Geophysical Research.

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